



US011668221B2

(12) **United States Patent**  
**Hruby et al.**

(10) **Patent No.:** **US 11,668,221 B2**  
(45) **Date of Patent:** **Jun. 6, 2023**

(54) **EXHAUST GAS TREATMENT SYSTEM AND METHOD WITH FOUR-WAY CATALYZED FILTER ELEMENT**

(71) Applicant: **Deere & Company**, Moline, IL (US)

(72) Inventors: **Eric J. Hruby**, Waterloo, IA (US);  
**Ayyappan Ponnaiyan**, Waterloo, IA (US)

(73) Assignee: **Deere & Company**, Moline, IL (US)

(\* ) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **17/503,101**

(22) Filed: **Oct. 15, 2021**

(65) **Prior Publication Data**

US 2022/0034247 A1 Feb. 3, 2022

**Related U.S. Application Data**

(63) Continuation of application No. 16/456,740, filed on Jun. 28, 2019, now Pat. No. 11,187,127.

(51) **Int. Cl.**  
**F01N 3/20** (2006.01)  
**F01N 3/029** (2006.01)  
(Continued)

(52) **U.S. Cl.**  
CPC ..... **F01N 3/208** (2013.01); **F01N 3/0293** (2013.01); **F01N 3/0885** (2013.01);  
(Continued)

(58) **Field of Classification Search**  
CPC .. F01N 3/2066; F01N 3/208; F01N 2510/068; F01N 2510/0682; F01N 2610/02  
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

6,093,378 A 7/2000 Deeba et al.  
6,753,294 B1 6/2004 Brisley et al.  
(Continued)

FOREIGN PATENT DOCUMENTS

DE 102015116659 A1 4/2017  
EP 2426326 A1 3/2012  
(Continued)

OTHER PUBLICATIONS

European Search Report Issued in Counterpart Application No. 20181950.5 dated Nov. 9, 2020 (7 pages).

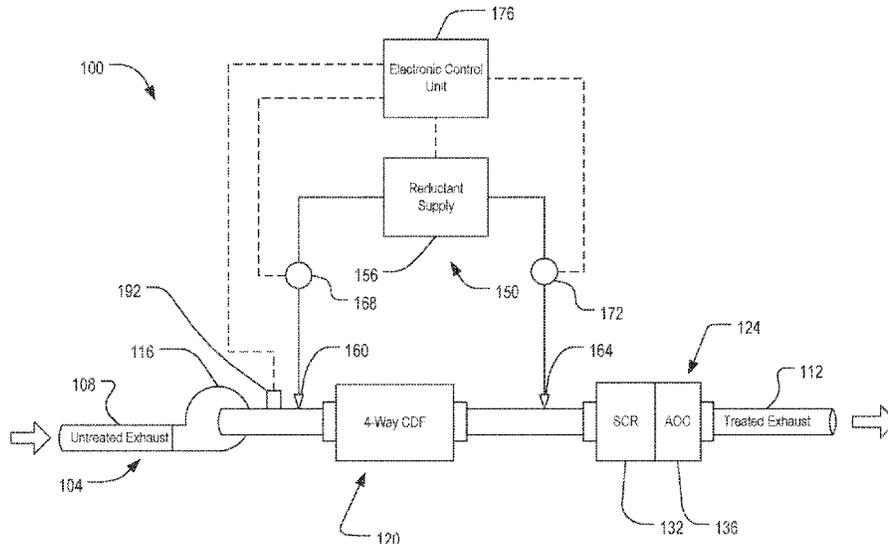
*Primary Examiner* — Jonathan R Matthias

(74) *Attorney, Agent, or Firm* — Michael Best & Friedrich LLP

(57) **ABSTRACT**

An exhaust gas treatment system for an internal combustion engine includes an exhaust gas pathway configured to receive exhaust gas from the internal combustion engine, a first treatment element positioned within the exhaust gas pathway, a first injector configured to introduce a first reductant into the exhaust gas pathway upstream of the first treatment element, a second injector configured to introduce a second reductant into the exhaust gas pathway downstream of the first treatment element, a second treatment element positioned within the exhaust gas pathway downstream of the second injector, the second treatment element including a SCR element, and a controller configured to periodically initiate a desulfuring regeneration cycle by increasing a concentration of hydrocarbons in the exhaust gas and increasing the flow of the first reductant through the first injector to oxidize sulfur contamination in the first treatment element at temperatures between 400 and 500 degrees Celsius.

**19 Claims, 5 Drawing Sheets**



(51)	<b>Int. Cl.</b> <b>F01N 3/08</b> (2006.01) <i>B01D 53/94</i> (2006.01) <i>F01N 1/08</i> (2006.01) <i>F01N 13/00</i> (2010.01)	2015/0247437 A1* 9/2015 Ancimer ..... F01N 3/2033 60/297 2015/0275730 A1* 10/2015 Gupta ..... B01D 53/9486 60/276 2016/0090485 A1 3/2016 Schwalm et al. 2016/0121267 A1 5/2016 Schoenhaber et al. 2016/0193597 A1 7/2016 Wolff et al. 2016/0215162 A1 7/2016 Clausse et al. 2017/0014766 A1 1/2017 Schoenhaber et al. 2017/0130628 A1 5/2017 Franz et al. 2017/0204762 A1 7/2017 Kotrba et al. 2017/0296969 A1 10/2017 Ohashi et al. 2017/0327626 A1 11/2017 Roller et al. 2018/0021757 A1 1/2018 Karpov et al. 2018/0080357 A1 3/2018 Jung et al. 2018/0086938 A1 3/2018 Schaefer et al. 2018/0087426 A1 3/2018 Dou et al. 2018/0111088 A1 4/2018 Li et al. 2018/0111089 A1 4/2018 Li et al. 2018/0135482 A1 5/2018 Bailey 2018/0163596 A1* 6/2018 Punke ..... F01N 13/009 2018/0163597 A1* 6/2018 Xue ..... B01D 53/9472 2018/0171174 A1 6/2018 Schaefer et al. 2018/0185788 A1 7/2018 Grubert et al. 2018/0195425 A1 7/2018 Li et al. 2018/0353905 A1 12/2018 Li et al. 2019/0001268 A1 1/2019 Chen et al. 2019/0153921 A1 5/2019 Gerlach et al. 2020/0224576 A1 7/2020 Dou et al. 2020/0230582 A1 7/2020 Patchett et al.
(52)	<b>U.S. Cl.</b> CPC ..... <b>F01N 3/2066</b> (2013.01); <i>B01D 53/9459</i> (2013.01); <i>F01N 1/082</i> (2013.01); <i>F01N</i> <i>13/009</i> (2014.06); <i>F01N 2250/02</i> (2013.01); <i>F01N 2510/0682</i> (2013.01); <i>F01N 2610/02</i> (2013.01); <i>F01N 2900/1404</i> (2013.01)	
(56)	<b>References Cited</b>  U.S. PATENT DOCUMENTS  6,935,105 B1 8/2005 Page et al. 8,557,204 B2 10/2013 Nunan et al. 8,722,000 B2 5/2014 Boorse 2006/0156709 A1 7/2006 Twigg et al. 2008/0256935 A1 10/2008 Oger et al. 2009/0151340 A1 6/2009 Kato 2010/0064662 A1 3/2010 Hinz et al. 2010/0175372 A1 7/2010 Lambert et al. 2011/0036560 A1 2/2011 Vail, III et al. 2011/0078997 A1 4/2011 Boorse et al. 2011/0179777 A1 7/2011 Chandler et al. 2011/0237684 A1 9/2011 Ebel et al. 2012/0045586 A1 2/2012 Hoffmann et al. 2013/0210609 A1 8/2013 Johansen 2014/0161981 A1 6/2014 Westhoff et al. 2014/0263190 A1 9/2014 Biberger et al. 2014/0271429 A1 9/2014 Kazi et al. 2014/0308451 A1 10/2014 Westhoff et al. 2014/0322448 A1 10/2014 Hoffmann et al. 2014/0369912 A1 12/2014 Zheng et al. 2015/0018197 A1 1/2015 Hsieh et al. 2015/0210886 A1 7/2015 Hoffmann et al. 2015/0240085 A1 8/2015 Klein et al. 2015/0247050 A1 9/2015 Hoffmann et al.	
		<b>FOREIGN PATENT DOCUMENTS</b>  WO WO201117360 A2 9/2011 WO WO2016050396 A1 4/2016 WO 2017034463 A1 3/2017 WO WO2018022211 A1 2/2018 WO WO2018024546 A1 2/2018 WO WO2018024547 A1 2/2018 WO WO2018154463 A1 8/2018 WO WO2018197541 A1 11/2018  * cited by examiner

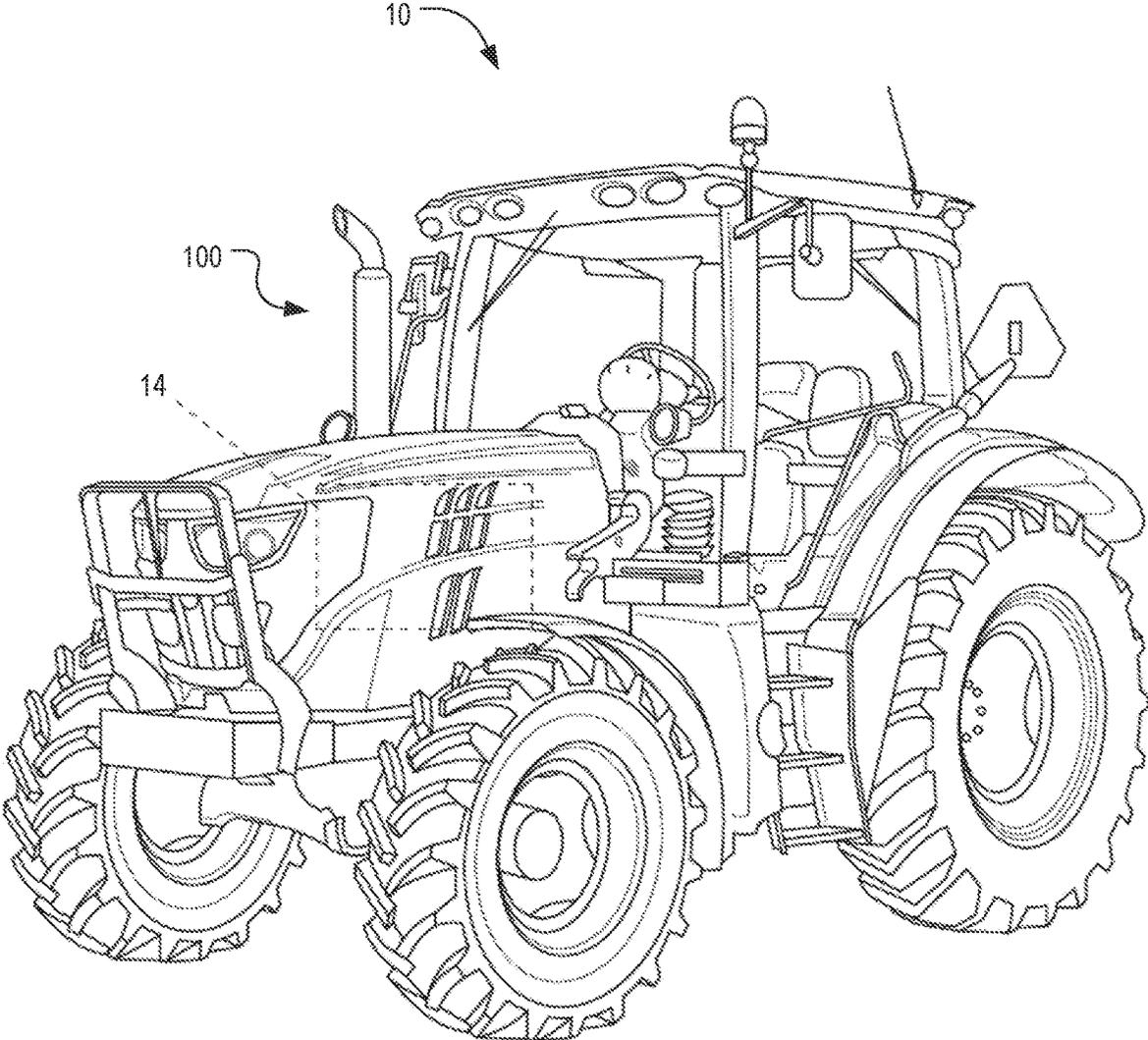


FIG. 1

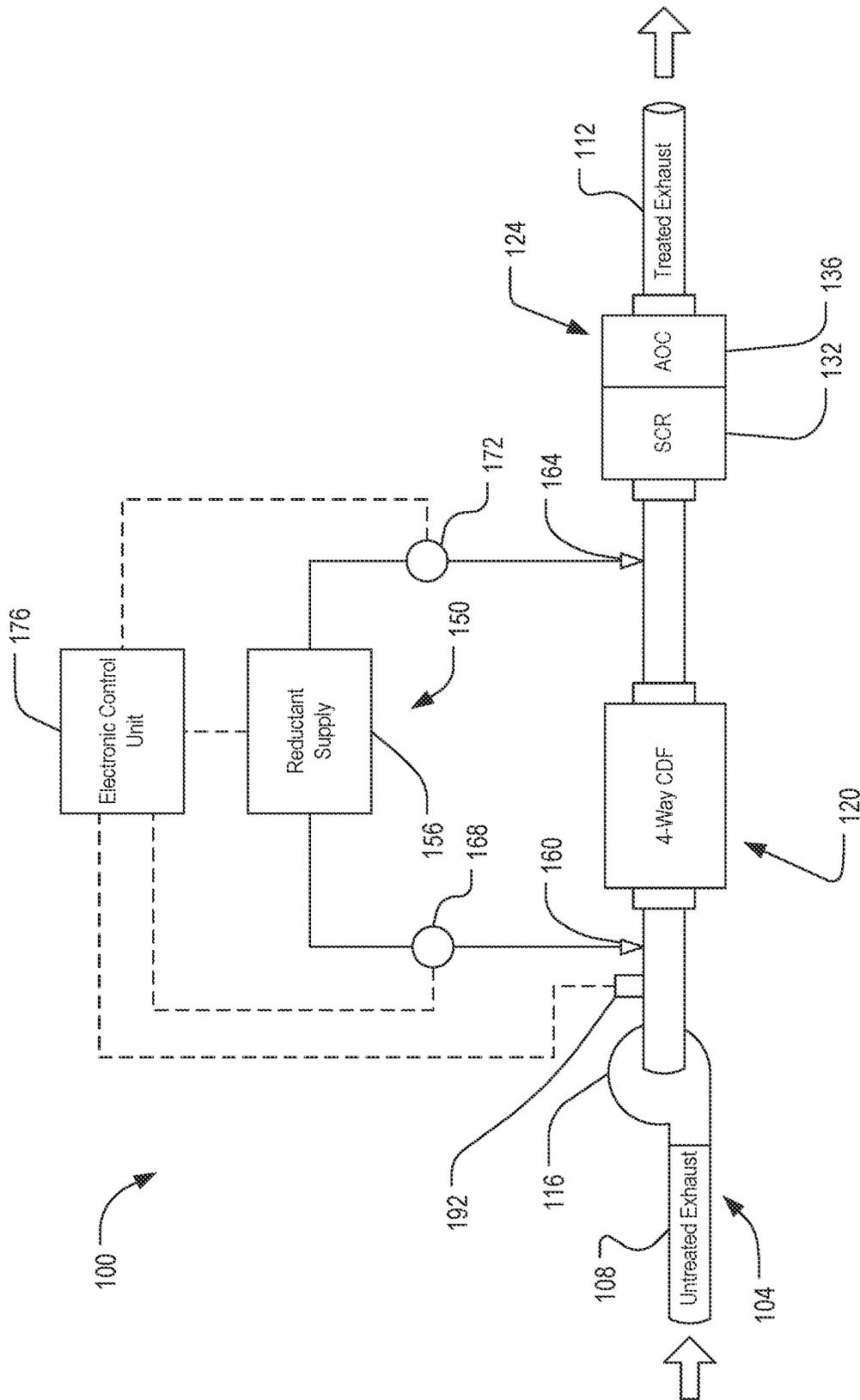


FIG. 2

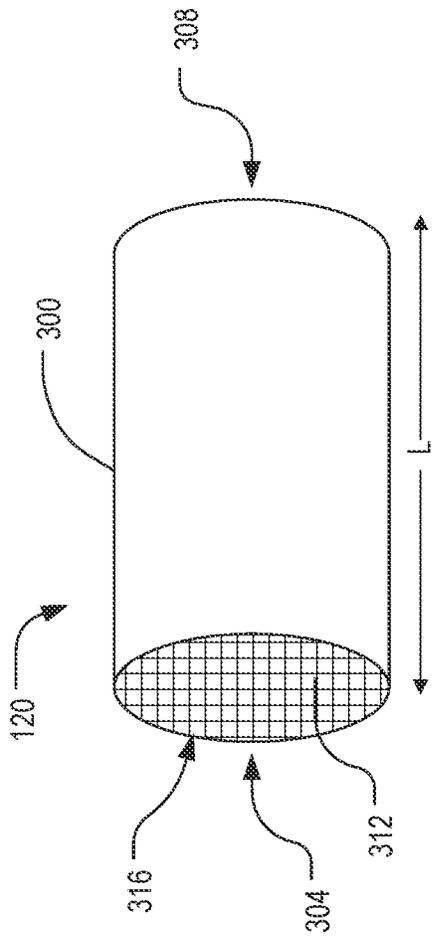


FIG. 3

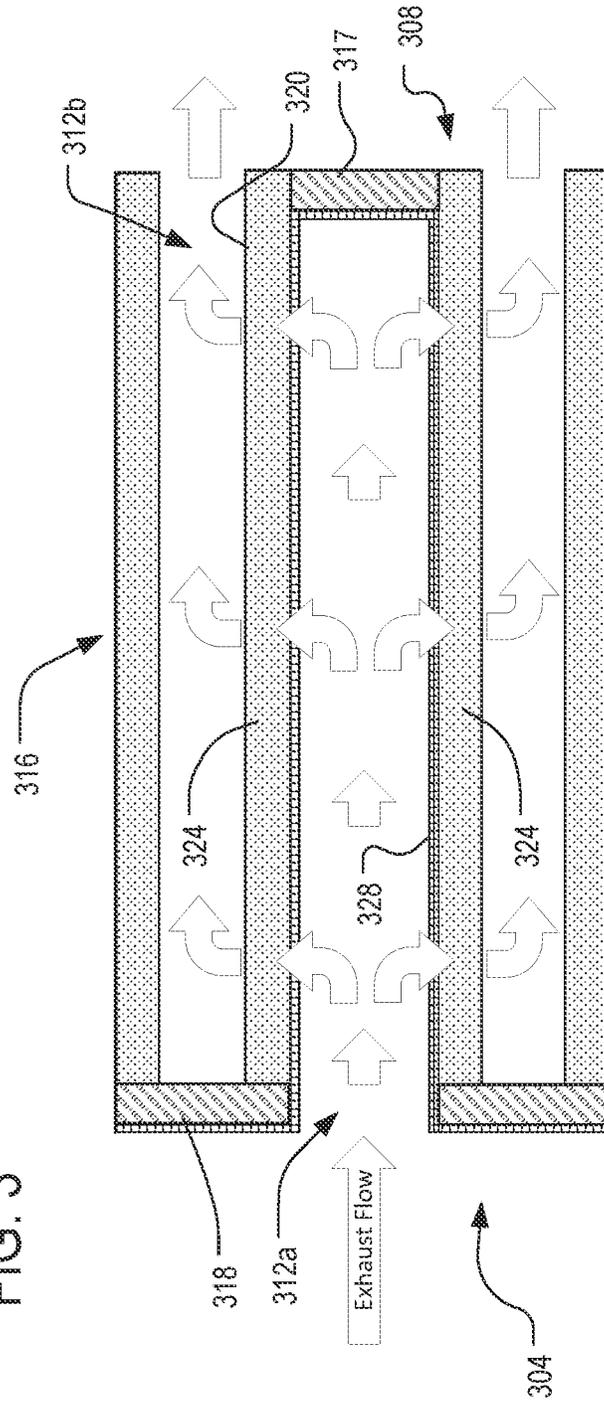


FIG. 4

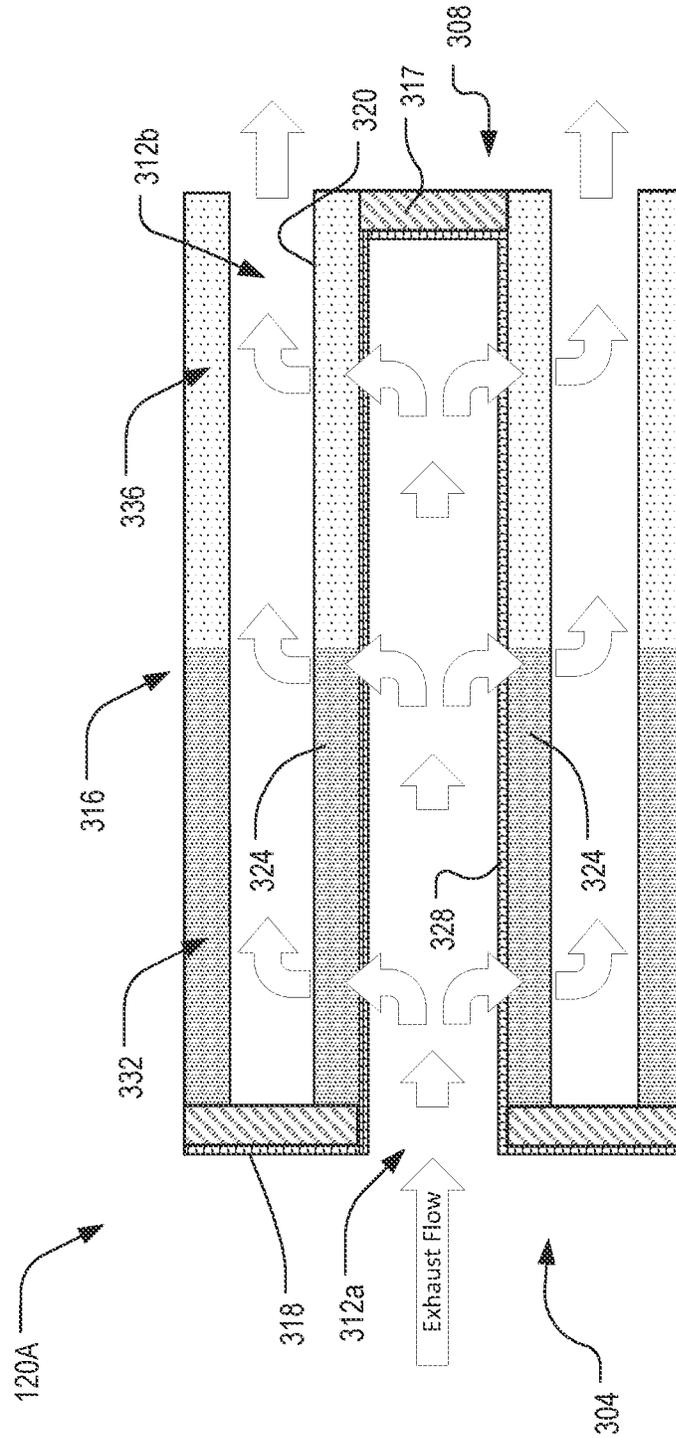


FIG. 5

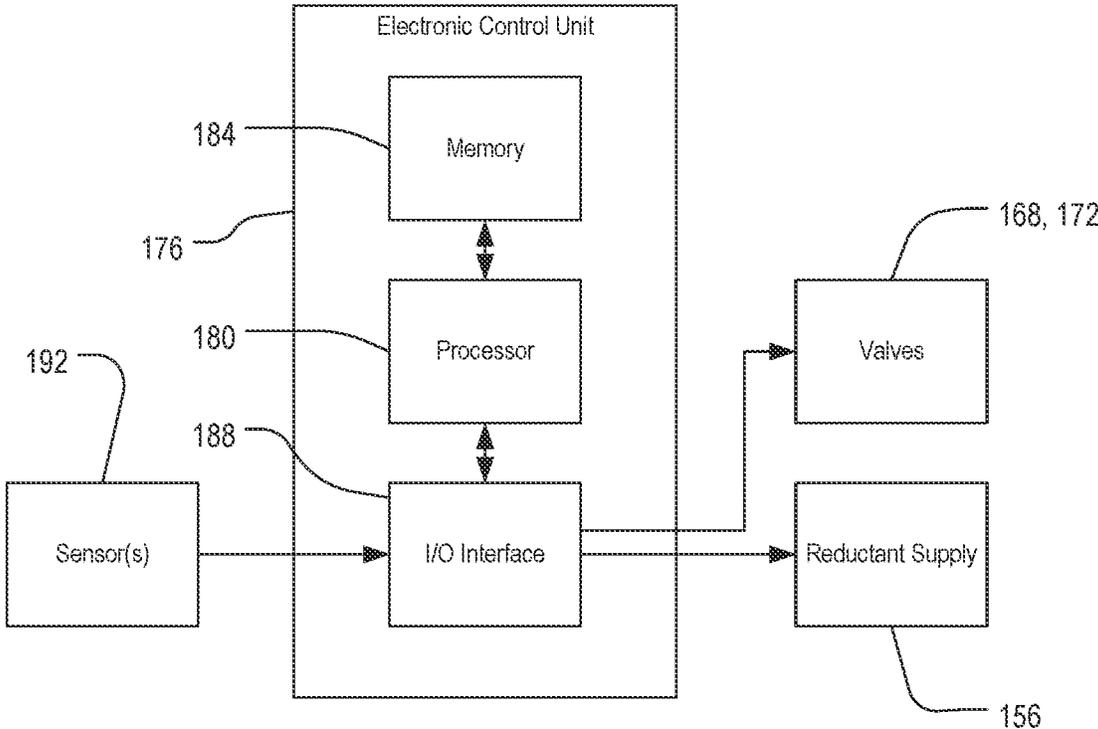


FIG. 6

1

## EXHAUST GAS TREATMENT SYSTEM AND METHOD WITH FOUR-WAY CATALYZED FILTER ELEMENT

### CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of co-pending U.S. patent application Ser. No. 16/456,740, filed Jun. 28, 2019, the entire content of which is incorporated herein by reference.

### BACKGROUND

The present disclosure relates to exhaust systems and more particularly to diesel exhaust gas treatment systems.

Diesel exhaust is subject to emissions regulations covering a variety of emission components, including particulate matter and nitrogen oxides (NOx). A variety of exhaust treatment devices have been developed to reduce these emission components. For example, a selective catalytic reduction (SCR) element can be used to convert the NOx present in exhaust gas into other compounds, such as nitrogen, water, and carbon dioxide.

Typically, diesel exhaust fluid (DEF)—a solution of urea and deionized water—is injected upstream of the SCR element to provide ammonia, which acts as a reducing agent and reacts with the NOx in the presence of the SCR catalyst in accordance with Equation (1):



The NOx and ammonia are thus converted into nitrogen and water. As evident from Equation (1), the optimal stoichiometric ratio for this reaction includes equal parts of nitric oxide (NO) and nitrogen dioxide (NO<sub>2</sub>).

Particulate matter is another component of diesel exhaust emissions being targeted with increasingly stringent regulations. A diesel particulate filter (DPF) can be used to trap diesel particulate matter. During operation, trapped soot on the filter element can be oxidized through a process referred to as passive regeneration. In particular, during passive regeneration, the carbon-based soot reacts with NO<sub>2</sub> in accordance with Equation (2) and Equation (3):



As evident from Equations (2) and (3), NO<sub>2</sub> also plays an important role in soot oxidation.

To provide enough NO<sub>2</sub> for NOx reduction and soot oxidation, some emissions systems include a diesel oxidation catalyst (DOC) upstream of a SCR and a DPF element. The DOC includes one or more precious group metals (e.g., platinum, palladium, etc.) that act as a catalyst to reduce emission of carbon monoxide, hydrocarbons, and volatile organic compounds. The DOC also oxidizes NO to NO<sub>2</sub>, which promotes faster SCR reactions and enhances passive regeneration.

At low temperatures (e.g., about 200 degrees Celsius or less) that occur during a cold start state of the engine or during very cold ambient operating conditions, the DOC may consume NO<sub>2</sub> by reacting NO<sub>2</sub> with carbon monoxide and hydrocarbons in the exhaust gas. This reduces the efficacy of downstream SCR elements, which require the presence of NO<sub>2</sub>. The DOC also adds thermal mass to the exhaust gas treatment system, which delays warm-up of the downstream SCR elements.

2

In typical exhaust treatment systems with a DPF, passive regeneration alone may not be sufficient to manage soot accumulation on the filter element. Accordingly, such systems may periodically employ active regeneration. During active regeneration, a temperature of the exhaust gas at the DPF is increased to a target elevated temperature, typically at least 600 degrees Celsius, and maintained at the elevated temperature for a predetermined time period (e.g., 30 minutes). At high temperatures, carbon-based soot reacts with oxygen in accordance with Equation (4) and Equation (5):



The reactions of Equations (4) and (5) during active regeneration will thus restore the DPF to a clean state.

Raising the temperature of the exhaust gas during active regeneration requires using additional fuel, which is oxidized in the DOC. This increases CO<sub>2</sub> emissions. In addition, because the DPF is positioned downstream of the DOC, the temperature of the exhaust gas must be even higher in the DOC to achieve sufficiently high temperatures in the DPF for active regeneration to occur. The high temperatures increase insulation requirements, adding size, weight, and cost to the exhaust treatment system.

### SUMMARY

Low temperature NOx reduction and CO<sub>2</sub> emissions are increasingly important considerations as emissions regulations become more stringent. Accordingly, a need exists for an exhaust gas treatment system able to more effectively reduce NOx and other emission components from exhaust gas.

The present disclosure provides, in one aspect, an exhaust gas treatment system for an internal combustion engine including an exhaust gas pathway configured to receive exhaust gas from the internal combustion engine, a first treatment element positioned within the exhaust gas pathway, a first injector configured to introduce a first reductant into the exhaust gas pathway upstream of the first treatment element, a second injector configured to introduce a second reductant into the exhaust gas pathway downstream of the first treatment element, a second treatment element positioned within the exhaust gas pathway downstream of the second injector, the second treatment element including a SCR element, and a controller configured to periodically initiate a desulfuring regeneration cycle by increasing a concentration of hydrocarbons in the exhaust gas and increasing the flow of the first reductant through the first injector to oxidize sulfur contamination in the first treatment element at temperatures between 400 and 500 degrees Celsius.

The present disclosure provides, in another aspect, an exhaust gas treatment system for an internal combustion engine including an exhaust gas pathway configured to receive exhaust gas from the internal combustion engine, a first injector configured to selectively introduce a first reductant into the exhaust gas pathway in response to a sensed temperature of the exhaust gas being within a predetermined temperature range, and a first treatment element positioned within the exhaust gas pathway downstream of the first injector. The first treatment element includes a selective catalytic reduction (SCR) layer, a porous filter substrate, and a precious metal catalyst layer. The exhaust gas treatment system also includes a second treatment element positioned within the exhaust gas pathway downstream of the first

treatment element, the second treatment element including a SCR element, and a controller configured to periodically initiate a desulfuring regeneration cycle by increasing a concentration of hydrocarbons in the exhaust gas and increasing the flow of the first reductant through the first injector to oxidize sulfur contamination in the first treatment element at temperatures between 400 and 500 degrees Celsius.

The present disclosure provides, in another aspect, an exhaust gas treatment system for an internal combustion engine including an exhaust gas pathway configured to receive exhaust gas from the internal combustion engine, a first injector configured to introduce a first reductant into the exhaust gas pathway, and a first treatment element positioned within the exhaust gas pathway downstream of the first injector. The first treatment element includes an inlet channel, an outlet channel, a selective catalytic reduction (SCR) layer, a NO<sub>x</sub> storage layer coated under or over the SCR layer, a porous filter substrate including a porous filter wall separating the inlet channel and the outlet channel such that the exhaust gas is configured to flow from the inlet channel to the outlet channel through the porous filter wall, and a precious metal catalyst layer coated on the porous filter substrate such that the precious metal catalyst layer fully infiltrates the porous filter wall. The exhaust gas treatment system also includes a controller configured to periodically initiate a desulfuring regeneration cycle by increasing a concentration of hydrocarbons in the exhaust gas and increasing the flow of the first reductant through the first injector to oxidize sulfur contamination in the first treatment element at temperatures between 400 and 500 degrees Celsius. The porous filter substrate is configured to capture soot from the exhaust gas, and the precious metal catalyst layer is configured to exothermically react hydrocarbons from the exhaust gas to promote oxidation of the captured soot on the porous filter substrate through active regeneration.

Any of the above referenced aspects of the disclosure can be combined with any one or more of the above referenced aspects of the disclosure. Other aspects of the disclosure will become apparent by consideration of the detailed description and accompanying drawings.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective view of a vehicle in which the disclosed exhaust gas treatment system and method with improved regeneration may be implemented.

FIG. 2 is a schematic diagram of an exhaust gas treatment system according to an embodiment of the present disclosure.

FIG. 3 is a perspective view of a four-way catalyzed diesel filter of the exhaust gas treatment system of FIG. 2.

FIG. 4 is a cross-sectional view of a portion of the four-way catalyzed diesel filter of FIG. 3.

FIG. 5 is a cross-sectional view of a portion of a four-way catalyzed diesel filter according to another embodiment.

FIG. 6 is a schematic diagram of an electronic control unit of the exhaust gas treatment system of FIG. 2.

Before any embodiments of the disclosure are explained in detail, it is to be understood that the disclosure is not limited in its application to the details of construction and the arrangement of components set forth in the following description or illustrated in the accompanying drawings. The

disclosure is capable of supporting other embodiments and of being practiced or of being carried out in various ways.

#### DETAILED DESCRIPTION

FIG. 1 illustrates an exemplary vehicle 10 including a diesel-powered internal combustion engine 14 and an exhaust gas treatment system 100 according to one embodiment. The illustrated vehicle 10 is a utility tractor, but the exhaust gas treatment system 100 is not so limited in application and can be used in conjunction with any diesel-powered internal combustion engine. For example, the exhaust gas treatment system 100 can be used in other work vehicles, passenger vehicles, or other equipment powered by a diesel engine (e.g., generators, compressors, pumps, and the like).

With reference to FIG. 2, the exhaust gas treatment system 100 includes an exhaust pathway 104 (e.g., an exhaust pipe) having an inlet or upstream side 108 that receives untreated exhaust gas from the engine 14 and an outlet or downstream side 112 through which treated exhaust gas is discharged. A turbocharger 116 is disposed in the exhaust pathway 104 proximate the inlet 108, but in alternative embodiments, the turbocharger 116 may be omitted. In some embodiments, multiple turbochargers 116 may be provided in the exhaust pathway 104.

A first treatment element 120 and a second treatment element 124 are located in series along the exhaust pathway 104, between the inlet 108 and the outlet 112. Although the second treatment element 124 is located downstream of the first treatment element 120 in the illustrated embodiment, the numeric designations “first,” “second,” etc. are used herein for convenience and should not be regarded as defining order, quantity, or relative position. In addition, the illustrated first and second treatment elements 120, 124 are located downstream of the turbocharger 116. In other embodiments, however, the turbocharger 116 may be located between the first and second treatment elements 120, 124 or downstream of the treatment elements 120, 124.

Referring to FIGS. 3 and 4, the first treatment element 120 in the illustrated embodiment is a four-way catalyzed diesel filter (CDF) that is close-coupled to the engine 14. The first treatment element 120 includes a cylindrical housing 300 with an inlet end 304, an outlet end 308 downstream of the inlet end 304, and a plurality of channels 312 extending between the inlet end 304 and the outlet end 308. The distance between the inlet end 304 and the outlet end 308 defines a length L of the first treatment element 120 (FIG. 3).

The channels 312 are arranged in a grid pattern or honeycomb pattern to form a filter substrate 316 of the first treatment element 120. In the illustrated embodiment, the filter substrate 316 is a monolithic element made of a highly heat-resistant material, such as ceramic. Adjacent channels 312 are blocked at alternating ends. That is, the inlet end 304 of a first channel 312a is open to receive incoming exhaust gas flowing along the exhaust gas pathway 104, and the outlet end 308 of the first channel 312a is blocked by an outlet end wall 317 (FIG. 4). The inlet end 304 of an adjacent second channel 312b is blocked by an inlet end wall 318, and the outlet end 308 of the second channel 312b is open to discharge exhaust gas from the first treatment element 120.

With reference to FIG. 4, a porous wall 320 extends between the inlet end 304 and the outlet end 308 and separates the adjacent channels 312a, 312b. Accordingly, exhaust gas that enters the inlet end 304 of the first channel 312a is forced through the porous wall 320 and into the second channel 312b before exiting the first treatment ele-

ment **120**. The porous wall **320** captures particulate matter from the exhaust gas. As such, the first treatment element **120** functions as a diesel particulate filter (DPF).

In the illustrated embodiment, the first treatment element **120** further includes a precious metal catalyst layer **324** and a selective catalytic reduction (SCR) layer **328**. The precious metal catalyst layer **324** includes precious metal catalyst material (e.g., platinum, palladium, a combination of platinum and palladium, etc.) coated on each of the porous walls **320** of the filter substrate **316**. The precious metal catalyst layer **324** includes a precious metal catalyst concentration or loading between about 5 grams and about 20 grams of the precious metal catalyst material per cubic foot of the filter substrate **316**. In the illustrated embodiment, the precious metal catalyst concentration in the precious metal catalyst layer **324** is substantially uniform along the length L of the first treatment element **120**. In other embodiments, the precious metal catalyst concentration in the precious metal catalyst layer **324** may vary along the length L of the first treatment element **120**. The precious metal catalyst layer **324** may be applied to the walls **320** as a wash coat, via ion-exchange, or any other suitable process. In some embodiments, the precious metal catalyst layer **324** may fully infiltrate each of the walls **320**. In other embodiments, the precious metal catalyst layer **324** may extend only partially through the thickness of each of the walls **320**.

The precious metal catalyst layer **324** provides the first treatment element **120** with the functionality of a diesel oxidation catalyst (DOC). In particular, the precious metal catalyst layer **324** may oxidize carbon monoxide (CO) from exhaust passing through the first treatment element **120** into carbon dioxide (CO<sub>2</sub>). The precious metal catalyst layer **324** may also exothermically oxidize any hydrocarbons in the exhaust gas to carbon dioxide and water, which raises the temperature of the exhaust gas as it passes through first treatment element **120**. Finally, the precious metal catalyst layer **324** may oxidize nitric oxide (NO) to nitrogen dioxide (NO<sub>2</sub>).

With continued reference to FIG. 4, the SCR layer **328** lines each of the inlet channels **312a** of the first treatment element **120** and provides the first treatment element **120** with NOx reduction capabilities. For example, the illustrated SCR layer **328** is coated on the inlet channel side of the porous walls **320** and on the inlet channel side of the outlet end wall **317**. In the illustrated embodiment, the SCR layer **328** is also coated on the upstream side of each of the inlet end walls **318**. The SCR layer **328** extends along at least 5% of the length L of the first treatment element **120**, and the illustrated SCR layer **328** extends along substantially the entire length L of the first treatment element **120**. In some embodiments, the SCR layer **328** may be impregnated into the pores of the porous walls **320**, either partially or entirely through the thickness of each of the walls **320**.

The SCR layer **328** includes SCR catalyst material, which may include one or more base metal oxides, such as Al<sub>2</sub>O<sub>3</sub>, SiO<sub>2</sub>, TiO<sub>2</sub>, CeO<sub>2</sub>, ZrO<sub>2</sub>, V<sub>2</sub>O<sub>5</sub>, La<sub>2</sub>O<sub>3</sub>. Alternatively or additionally, the SCR layer **328** may include one or more zeolites, such as Fe-zeolite, Cu-zeolite, blends of Fe-zeolite and Cu-zeolite, or Ce-zeolite. The SCR layer **328** includes an SCR catalyst concentration or loading between about 5 grams and about 100 grams of SCR catalyst material per liter of the filter substrate **316**. In the illustrated embodiment, the SCR catalyst concentration in the SCR layer **328** is substantially uniform along the length L of the first treatment element **120**. In other embodiments, the SCR catalyst concentration in the SCR layer **328** may vary along the length L of the first treatment element **120**. The SCR layer **328** is

preferably applied as a wash coat after the precious metal catalyst layer **324**; however, the SCR layer **328** may be applied in other ways.

In some embodiments, the first treatment element **120** may also include a NOx storage layer (not shown) coated on to the substrate **316**, either under or over the SCR layer **328**. The NOx storage layer captures and stores NOx at temperatures within a first temperature range (e.g., between about 100 degrees Celsius and about 300 degrees Celsius in some embodiments, or between about 100 degrees Celsius and about 250 degrees Celsius in other embodiments). That is, the NOx storage layer captures and stores NOx at relatively low temperatures experienced during cold start or cold ambient operating conditions. The NOx storage layer releases the stored NOx at temperatures above the first temperature range, once the exhaust gas treatment system **100** has heated up.

In some embodiments, the NOx storage layer may include a passive NOx adsorber (PNA). In such embodiments, the NOx storage layer includes a zeolite, and preferably a small pore zeolite such as Chabazite or Linde Type A (LTA) that is thermally stable at temperatures up to at least 700 degrees Celsius. Palladium, platinum, or, in some embodiments, a mixture of precious metals, is dispersed on the zeolite. The precious metal can be dispersed on the zeolite by ion-exchange, adsorption, impregnation, or any other suitable method, such that precious metal ions are dispersed into the pores of the zeolite. The zeolite acts a molecular sieve such that only small molecules such as NH<sub>3</sub>, NO, and NO<sub>2</sub> able to enter freely into the molecular structure of the zeolite. The precious metal ions dispersed in the zeolite store NOx and NH<sub>3</sub> by adsorption.

In other embodiments, the NOx storage layer may include a NOx storage catalyst. In such embodiments, the NOx storage layer includes a precious metal catalyst (e.g., platinum or palladium) coated on a base metal oxide, such as barium-aluminum oxide. The precious metal catalyst is configured to oxidize nitric oxide (NO) to nitrogen dioxide (NO<sub>2</sub>), which then forms nitrates with the base metal oxide to effectively capture and store NOx.

The NOx storage layer allows for improved low temperature NOx reduction by capturing and storing NOx at low temperatures when the NOx reduction efficiency of the SCR layer **328** is reduced. When the stored NOx is later released at higher temperatures, the additional NOx may enhance passive regeneration of the filter substrate **316** before being reduced by the SCR layer **328**.

FIG. 5 illustrates a first treatment element **120A** according to another embodiment. The first treatment element **120A** is similar to the first treatment element **120** and may be incorporated into the exhaust gas treatment system **100** of FIG. 2. Features of the first treatment element **120A** corresponding with features of the first treatment element **120** are given corresponding reference numbers. In addition, the following description focuses primarily on the differences between the first treatment element **120A** and the first treatment element **120**.

The filter substrate **316** of the first treatment element **120A** includes a first or upstream portion **332** and a second or downstream portion **336**. The concentration of precious metal catalyst material in the precious metal catalyst layer **324** differs in the first portion **332** and the second portion **336**. For example, in the illustrated embodiment, precious metal catalyst layer **324** has a precious metal catalyst concentration in the first portion **332** between about 6 grams and about 40 grams of the precious metal catalyst material per cubic foot of the filter substrate **316**. The precious metal

catalyst layer **324** has a precious metal catalyst concentration in the second portion **336** between about 5 grams and about 20 grams of the precious metal catalyst material per cubic foot of the filter substrate **316**. Thus, the precious metal catalyst concentration in the first portion **332** may be at least about 1.2 times greater than the precious metal catalyst concentration in the second portion **336**. The precious metal catalyst material may include, for example, platinum or palladium. In some embodiments, the precious metal catalyst material may include a mixture of platinum and palladium. In such embodiments, the ratio of platinum to palladium in the first portion **332** may be the same or different as the ratio of platinum to palladium in the second portion **336**.

In some embodiments, the lengths of the first and second portions **332**, **336** are equal. For example, each of the first portion **332** and the second portion **336** may extend about 50% of the total length *L* of the first treatment element **120A**. In other embodiments, the first portion **332** extends between about 5% and about 50% of the length *L* of the first treatment element **120A**, and the second portion **336** extends between about 50% and about 95% of the length *L* of the first treatment element **120A**. In other embodiments, the first portion **332** extends between about 5% and about 25% of the length *L* of the first treatment element **120A**, and the second portion **336** extends between about 75% and about 95% of the length *L* of the first treatment element **120A**. By including a higher concentration of precious metal catalyst material in the first portion **332**, catalytic heating (e.g., due to oxidation of hydrocarbons in the exhaust gas) is increased, which enhances the NO<sub>x</sub> reduction performance of the SCR layer **328**.

With reference to FIG. 2, the second treatment element **124** in the illustrated embodiment includes an SCR element **132** and an ammonia oxidation catalyst (AOC) **136**. The SCR element **132** includes a catalytic washcoat on a monolithic support material, such as ceramic. The washcoat includes one or more metal catalysts, such as a copper-based catalyst, an iron-based catalyst, or a vanadium-based catalyst. Alternatively, other washcoats (e.g., zeolite-based) may be used.

The SCR element **132** and the AOC **136** are positioned in series, with the AOC **136** located downstream of the SCR element **132**. The SCR element **132** reduces NO<sub>x</sub> from exhaust gas passing through it. The AOC **136** converts excess ammonia leaving the SCR element **132** to nitrogen and water. The SCR element **132** and the AOC **136** are packaged together within a common housing, as illustrated in FIG. 2. In some embodiments, the AOC **136** may be provided as a separate treatment element positioned downstream of the second treatment element **128**. In other embodiments, either or both the SCR element **132** and the AOC **136** may be omitted and optionally replaced by other exhaust treatment elements.

With continued reference to FIG. 2, the exhaust gas treatment system **100** further includes a reductant system **150** with a reductant supply **156** configured to supply reductant into the exhaust gas pathway **104**. The reductant supply **156** includes a reservoir for storing a reductant, such as diesel exhaust fluid (DEF) or ammonia. In some embodiments, the reductant supply **156** may include an ammonia generator configured to convert DEF into ammonia.

The reductant system **150** includes a first injector **160** and a second injector **164** in fluid communication with the reductant supply **156**. In some embodiments, the first injector **160** and the second injector **164** receive the same type of reductant from the reductant supply **156**. In other embodi-

ments, two different types of reductant (e.g., ammonia gas and DEF) may be provided to the first injector **160** and the second injector **164**, respectively.

The first injector **160** and the second injector **164** may be directly fluidly coupled to the reductant supply **156** (e.g., by independent conduits), or the first injector **160** and the second injector **164** may be fluidly coupled to a branch line, manifold, or other fluid transfer structure. The first injector **160** is positioned to introduce reductant into the exhaust pathway **104** at a first location upstream of the first treatment element **120** (i.e. between the turbocharger **116** and the first treatment element **120**). The second injector **164** is positioned to introduce reductant into the exhaust pathway **104** at a second location downstream of the first treatment element **120** and upstream of the second treatment element **124** (i.e. between the first and second treatment elements **120**, **124**). The exhaust gas treatment system **100** may include one or more flow affecting features (not shown) to promote mixing of the reductant in the exhaust gas upstream of either or both the first treatment element **120** and the second treatment element **124**.

A first valve **168** is disposed between the reductant supply **156** and the first injector **160**, and a second valve **172** is disposed between the reductant supply **156** and the second injector **164**. In some embodiments, the first and second valves **168**, **172** can be incorporated into the respective injectors **160**, **164** or into the reductant supply **156**. Alternatively, each of the valves **168**, **172** may be replaced by a pump.

Each of the illustrated valves **168**, **172** is movable between a closed position in which the flow of reductant through the valve **168**, **172** is substantially inhibited, and an open position in which reductant can flow freely through the valve **168**, **172** (e.g., via solenoid actuators, pneumatic actuators, hydraulic actuators, or the like). In some embodiments, one or both of the valves **168**, **172** can also have at least one intermediate position, between the closed and open positions, in which the flow of reductant through the valve **168**, **172** is partially restricted. In some embodiments, one or both of the valves **168**, **172** can be modulated to vary the flow rate of reductant.

The exhaust gas treatment system **100** further includes an electronic control unit or ECU **176** that controls operation of the system **100**. Referring to FIG. 3, the ECU **176** includes a plurality of electrical and electronic components that provide power, operational control, and protection to the components and modules within the ECU **176**. In particular, the ECU **176** includes, among other things, an electronic processor **180** (e.g., a programmable microprocessor, microcontroller, or similar device), non-transitory, machine-readable memory **184**, and an input/output interface **188**. The electronic processor **180** is communicatively coupled to the memory **184** and configured to retrieve from memory **184** and execute, among other things, instructions related to the control processes and methods described herein. In other embodiments, the ECU **176** includes additional, fewer, or different components.

In the illustrated embodiment, the ECU **176** is communicatively coupled to the first valve **168**, the second valve **172**, and, in some embodiments, the reductant supply **156** (i.e. via the input/output interface **188**). The ECU **176** may also be configured to communicate with external systems including, for example, engine controls and/or operator controls.

The illustrated ECU **176** is communicatively coupled to a temperature sensor **192**, which in the illustrated embodiment is coupled to the exhaust pathway **104** at a location upstream

of the first treatment element **120** (FIG. 2). The temperature sensor **192** may be a thermistor, thermocouple, resistance temperature detector, infrared sensor, or any other sensor suitable for measuring the temperature of exhaust gas. All or a portion of the temperature sensor **192** may extend into the exhaust pathway **104** so as to be directly exposed to exhaust gas. Alternatively, the temperature sensor **192** may be located outside the exhaust pathway **104** and measure the temperature of the exhaust gas indirectly (e.g., by measuring the temperature of the exhaust pipe).

The sensor **192** provides a temperature signal (e.g., an electrical signal) to the ECU **176** associated with the temperature of the exhaust gas flowing through the exhaust gas pathway **104** at the position of the temperature sensor **192**. In the illustrated embodiment, the temperature signal is associated with the temperature of the exhaust gas entering the first treatment element **120**.

In operation, the ECU **176** periodically or continuously receives the temperature signal from the sensor **192** (e.g., via the input/output interface **188**), which is indicative of the temperature of the exhaust gas entering the first treatment element **120**. The ECU **176** uses the temperature signal to determine a sensed temperature of the exhaust gas. The ECU **176** then periodically or continuously compares the sensed temperature with a temperature range. In some embodiments, the temperature range is about 50 degrees Celsius to about 400 degrees Celsius in some embodiments, about 100 degrees Celsius to about 300 degrees Celsius in other embodiments, or about 150 degrees Celsius to about 300 degrees Celsius in other embodiments. The temperature range corresponds with a cold-start or cold-operating temperature range of the exhaust gas treatment system **100**. The temperature range may be predetermined and stored in memory **184** (FIG. 3), or the temperature range may be calculated and periodically or continuously modified by the ECU **176** in response to feedback from one or more additional sensors.

If the sensed temperature is within the temperature range, the ECU **176** sets the first injector **160** to dose reductant into the exhaust gas pathway **104** by opening the first valve **168** (FIG. 2). The reductant mixes with the exhaust gas and enters the first treatment element **120**. The SCR layer **328** converts NOx in the presence of ammonia from the reducing agent via the reaction of Equation (1). In embodiments of the first treatment element **120** that include a NOx storage layer, the NOx storage layer extracts and store NOx from the passing exhaust gas at the relatively low temperatures experienced within the cold-start temperature range. Because molecules of ammonia in the reductant are similar in size to NOx molecules, the ammonia can enter the pores of the NOx storage layer and react with stored NOx to form nitrogen and water. This regenerates the NOx storage layer and frees up molecular sites for additional NOx storage. The reaction is enhanced by the SCR layer **328**, which is coated together with the NOx storage layer over the flow-through filter substrate **316** of the first treatment element **120**.

The exhaust gas is then forced through the porous filter walls **320**, which capture soot and particulate matter from the exhaust gas. The precious metal catalyst layer **324** oxidizes carbon monoxide (CO) from exhaust passing through the first treatment element **120** into carbon dioxide (CO<sub>2</sub>). The precious metal catalyst layer **324** also exothermically oxidizes any hydrocarbons in the exhaust gas to carbon dioxide and water, which raises the temperature of the exhaust gas as it passes through first treatment element **120**. Finally, the precious metal catalyst layer **324** oxidizes

nitric oxide (NO) to nitrogen dioxide (NO<sub>2</sub>) and also oxidizes any residual unreacted ammonia to reduce ammonia slip.

Next, the exhaust gas flows through the SCR portion **132** and the AOC portion **136** of the second treatment element **124**. Because the second treatment element **124** is downstream of the first treatment element **120**, it warms up more slowly than the close-coupled first treatment element **120**. The first treatment element **120** is advantageously able to effectively reduce NOx during the cold-start temperature range, however, giving the second treatment element **124** time to warm up and increase its efficacy.

The ECU **176** continues to monitor the temperature sensor **192**. When the exhaust gas treatment system **100** has warmed up sufficiently such that the sensed temperature exceeds the cold-start temperature range (e.g., the sensed temperature is greater than 300 degrees Celsius in some embodiments), the ECU **176** shuts off or disables flow through the first injector **160**. For example, the ECU **176** may disable flow through the first injector **160** by closing the first valve **168**. In some embodiments, a minimal amount of reductant may continue to flow through the first injector **160** to keep the injector **160** cool and to reduce sulfur poisoning effects on the SCR layer **328**, particularly if the SCR layer **328** includes a copper base metal.

At elevated temperatures beyond the cold-start temperature range, ammonia may oxidize in the presence of the precious metal catalyst layer **324** in the first treatment element **120**. This may produce additional NOx, rather than reducing the NOx content of the exhaust gas as desired. The exhaust gas treatment system **100** avoids this reaction by stopping injection through the first injector **160** at temperatures above the cold-start temperature range. NOx reduction responsibility is then borne by the second treatment element **124**, which is now sufficiently warmed for effective NOx reduction.

When the second treatment element **124** is sufficiently warmed (e.g., as indicated by a temperature sensor proximate the second treatment element **124**, via software estimation based on other sensed temperatures, etc.), the ECU **176** sets the second injector **164** to dose reductant from the reductant supply **156** into the exhaust gas pathway **104**. For example, the ECU **176** may open the second valve **172** (FIG. 2) if the sensed temperature at the second treatment element **124** is greater than 200 degrees Celsius. The reductant includes ammonia, which reduces NOx in the SCR element **132** via the reaction of Equation (1). Any unreacted ammonia is subsequently oxidized in the AOC portion **136**. The treated exhaust then exits the exhaust gas treatment system **100** through the outlet **112**.

If the sensed temperature of the exhaust gas at the second treatment element **124** falls below the threshold temperature (e.g., about 200 degrees Celsius), the ECU **176** stops flow through the second injector **164** by closing the second valve **172**. This avoids the formation of urea deposits, which may occur at low temperatures. In some embodiments, a minimal amount of reductant may continue to flow through the second injector **164** to keep the injector **164** cool. In some embodiments, the ECU **176** may modulate flow of reductant through the second injector **164** to account for different levels of NOx in the exhaust gas (e.g., in response to feedback from a NOx concentration sensor; not shown).

The first treatment element **120** promotes passive regeneration of the filter substrate **316** at ordinary operating temperatures. Because the first treatment element **120** contains precious metal catalyst material in the precious metal catalyst layer **324**, it performs the functions of a diesel

## 11

oxidation catalyst (DOC). In particular, the precious metal catalyst material in the first treatment element **120** promotes oxidation of NO to NO<sub>2</sub>, thereby increasing a proportion of NO<sub>2</sub> in the exhaust gas. As evident from Equations (2) and (3), the higher proportion of NO<sub>2</sub> contributes to soot oxidation.

The ECU **176** may periodically initiate active regeneration cycles by dosing the exhaust gas with hydrocarbons (e.g., unburnt fuel) either in the cylinders of the engine **14** or between the engine **14** and the first treatment element **120**. The hydrocarbons in the exhaust gas that pass through the first treatment element **120** react with the precious metal catalyst material in the precious metal catalyst layer **324** and oxidize in an exothermic reaction. This can raise the temperature of the exhaust gas to temperatures of at least 500 degrees Celsius to oxidize soot trapped in the porous filter walls **320** via Equations (4) and (5).

In some embodiments, the ECU **176** may also periodically initiate desulfuring (deSOx) regeneration cycles by dosing the exhaust gas with hydrocarbons and initiating reductant injection through the first injector **160**. In the presence of ammonia, sulfur contamination that may build up in the first treatment element **120** is oxidized at lower temperatures (e.g., between 400-500 degrees Celsius) than without ammonia present (requiring temperatures between about 500-650 degrees Celsius).

Thus, the close-coupled first treatment element **120** combines the functionality of a DOC, a DPF, and an SCR element into a single treatment element. The first treatment element **120** provides the exhaust gas treatment system **100** with improved cold-start NOx reduction, along with other benefits including improved active and passive regeneration and desulfuring performance. Because these capabilities are combined in a single treatment element, the overall size, weight, thermal mass, and cost of the exhaust gas treatment system **100** can be reduced.

Various features of the disclosure are set forth in the following claims.

What is claimed is:

1. An exhaust gas treatment system for an internal combustion engine, the exhaust gas treatment system comprising:

- an exhaust gas pathway configured to receive exhaust gas from the internal combustion engine;
- a first treatment element positioned within the exhaust gas pathway,
- a first injector configured to introduce a first reductant into the exhaust gas pathway upstream of the first treatment element;
- a second injector configured to introduce a second reductant into the exhaust gas pathway downstream of the first treatment element;
- a second treatment element positioned within the exhaust gas pathway downstream of the second injector, the second treatment element including a SCR element; and
- a controller configured to periodically initiate a desulfuring regeneration cycle by increasing a concentration of hydrocarbons in the exhaust gas and increasing the flow of the first reductant through the first injector to oxidize sulfur contamination in the first treatment element at temperatures between 400 and 500 degrees Celsius.

2. The exhaust gas treatment system of claim 1, wherein the controller is further configured to control a flow of the first reductant through the first injector based on a temperature of the exhaust gas proximate the first treatment element, and to control a flow of the second reductant through the

## 12

second injector based on a temperature of the exhaust gas proximate the second treatment element.

3. The exhaust gas treatment system of claim 2, wherein the controller is further configured to reduce the flow of the first reductant when the temperature of the exhaust gas proximate the first treatment element exceeds a first threshold temperature.

4. The exhaust gas treatment system of claim 3, wherein the controller is further configured to increase the flow of the second reductant when the temperature of the exhaust gas proximate the second treatment element exceeds a second threshold temperature.

5. The exhaust gas treatment system of claim 1, wherein the first treatment element includes an inlet channel including a selective catalytic reduction (SCR) washcoat and a NOx storage layer coated under or over the SCR washcoat, an outlet channel, and a porous filter wall separating the inlet channel and the outlet channel such that the exhaust gas is configured to flow from the inlet channel to the outlet channel through the porous filter wall.

6. The exhaust gas treatment system of claim 5, wherein the porous filter wall includes an inlet side facing the inlet channel, an outlet side facing the outlet channel, and a precious metal catalyst layer fully infiltrating a thickness of the porous filter wall between the inlet side and the outlet side.

7. The exhaust gas treatment system of claim 6, wherein: the first treatment element includes an inlet end and an outlet end opposite the inlet end, the inlet channel extends from the inlet end toward the outlet end, the outlet channel extends from the outlet end toward the inlet end, a distance between the outlet end and the inlet end defines a length of the first treatment element, and a concentration of precious metal in the precious metal catalyst layer varies along the length of the first treatment element.

8. The exhaust gas treatment system of claim 7, wherein: the precious metal catalyst layer includes a first concentration of precious metal along a first portion of the length, the precious metal catalyst layer includes a second concentration of precious metal along a second portion of the length, and the first concentration is at least 20% greater than the second concentration.

9. The exhaust gas treatment system of claim 8, wherein: the inlet channel, the outlet channel, and the porous filter wall are integrally formed together as part of a monolithic filter substrate, the first concentration is between 6 grams of precious metal per cubic foot of filter substrate and 40 grams of precious metal per cubic foot of filter substrate, and the second concentration is between 5 grams of precious metal per cubic foot of filter substrate and 20 grams of the precious metal per cubic foot of filter substrate.

10. The exhaust gas treatment system of claim 5, wherein the NOx storage layer is configured to capture and store NOx at temperatures within a first temperature range and to release stored NOx at temperatures greater than the first temperature range.

11. The exhaust gas treatment system of claim 1, wherein the first treatment element includes

- an inlet channel,
- an outlet channel,
- a selective catalytic reduction (SCR) layer,

13

a NOx storage layer coated under or over the SCR layer,  
 a porous filter substrate including a porous filter wall  
 separating the inlet channel and the outlet channel such  
 that the exhaust gas is configured to flow from the inlet  
 channel to the outlet channel through the porous filter  
 wall, and  
 a precious metal catalyst layer coated on the porous filter  
 substrate such that the precious metal catalyst layer  
 fully infiltrates the porous filter wall,  
 wherein the porous filter substrate is configured to capture  
 soot from the exhaust gas, and  
 wherein the precious metal catalyst layer is configured to  
 exothermically react hydrocarbons from the exhaust  
 gas to promote oxidation of the captured soot on the  
 porous filter substrate through active regeneration.

12. The exhaust gas treatment system of claim 11, wherein  
 the precious metal catalyst layer is configured to oxidize  
 carbon monoxide (CO) to carbon dioxide (CO<sub>2</sub>), and  
 wherein the precious metal catalyst layer is configured to  
 oxidize nitric oxide (NO) to nitrogen dioxide (NO<sub>2</sub>) to  
 promote oxidation of the captured soot on the porous filter  
 substrate through passive regeneration.

13. The exhaust gas treatment system of claim 11, wherein  
 the SCR layer is located in the inlet channel, and wherein the  
 NOx storage layer includes a passive NOx adsorber (PNA)  
 configured to capture and store NOx at temperatures within  
 a first temperature range and to release stored NOx at  
 temperatures greater than the first temperature range.

14. The exhaust gas treatment system of claim 1, wherein  
 the first reductant includes diesel exhaust fluid or ammonia.

15. An exhaust gas treatment system for an internal  
 combustion engine, the exhaust gas treatment system com-  
 prising:

- an exhaust gas pathway configured to receive exhaust gas  
 from the internal combustion engine;
- a first injector configured to selectively introduce a first  
 reductant into the exhaust gas pathway in response to a

14

sensed temperature of the exhaust gas being within a  
 predetermined temperature range;  
 a first treatment element positioned within the exhaust gas  
 pathway downstream of the first injector, the first  
 treatment element including  
 a selective catalytic reduction (SCR) layer,  
 a porous filter substrate, and  
 a precious metal catalyst layer,  
 a second treatment element positioned within the exhaust  
 gas pathway downstream of the first treatment element,  
 the second treatment element including a SCR element;  
 and  
 a controller configured to periodically initiate a desulfur-  
 ing regeneration cycle by increasing a concentration of  
 hydrocarbons in the exhaust gas and increasing the flow  
 of the first reductant through the first injector to oxidize  
 sulfur contamination in the first treatment element at  
 temperatures between 400 and 500 degrees Celsius.

16. The exhaust gas treatment system of claim 15,  
 wherein the first treatment element includes a NOx storage  
 layer including a passive NOx adsorber (PNA) configured to  
 capture and store NOx at temperatures within a first tem-  
 perature range and to release stored NOx at temperatures  
 greater than the first temperature range.

17. The exhaust gas treatment system of claim 15,  
 wherein the NOx storage layer and the SCR layer are coated  
 together over the porous filter substrate.

18. The exhaust gas treatment system of claim 15, further  
 comprising a second injector configured to introduce a  
 second reductant into the exhaust gas pathway downstream  
 of the first treatment element.

19. The exhaust gas treatment system of claim 18,  
 wherein the second reductant is a different type of reductant  
 than the first reductant.

\* \* \* \* \*